THE FORMATION OF BROWN DWARFS AS EJECTED STELLAR EMBRYOS

Bo Reipurth[1] and Cathie Clarke[2]

1: Center for Astrophysics and Space Astronomy,
University of Colorado, Boulder, CO 80309
(reipurth@casa.colorado.edu)

2: Institute of Astronomy,
Madingley Road, Cambridge CB3 0HA, UK
(cclarke@ast.cam.ac.uk)
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ABSTRACT

We conjecture that brown dwarfs are substellar objects because they have been ejected from small newborn multiple systems which have decayed in dynamical interactions. In this view, brown dwarfs are stellar embryos for which the star formation process was aborted before the hydrostatic cores could build up enough mass to eventually start hydrogen burning. The disintegration of a small multiple system is a stochastic process, which can be described only in terms of the half-life of the decay. A stellar embryo competes with its siblings in order to accrete infalling matter, and the one that grows slowest is most likely to be ejected. With better luck, a brown dwarf would therefore have become a normal star. This interpretation of brown dwarfs readily explains the rarity of brown dwarfs as companions to normal stars (aka the "brown dwarf desert"), the absence of wide brown dwarf binaries, and the flattening of the low mass end of the initial mass function. Possible observational tests of this scenario include statistics of brown dwarfs near Class 0 sources, and the kinematics of brown dwarfs in star forming regions while they still retain a kinematic signature of their expulsion. Because the ejection process limits the amount of gas brought along in a disk, it is predicted that substellar equivalents to the classical T Tauri stars should be very rare.

Subject headings: stars: low-mass, brown dwarfs – stars: formation – stars: pre-main sequence – stars: luminosity function, mass function – binaries: general – instabilities

1. INTRODUCTION

The past few years have seen a wealth of discoveries of brown dwarfs, whose bona fide nature as substellar objects have been confirmed by the presence of lithium in their spectra (Rebolo, Martín, Magazzù 1992; Martín, Basri, Zapatero Osorio 1999). Numerous brown dwarfs have been found in clusters like the Pleiades (e.g. Stauffer et al. 1998, Martín et al. 2000), some have been found in star forming regions like Taurus and Orion (e.g. Comerón, Neuhäuser & Kaas 2000; Luhman et al. 2000), and a few have been found as companions to main sequence or evolved stars (e.g. Nakajima et al. 1996). Brown dwarfs are now also rapidly showing up in infrared surveys of field stars like DENIS and 2MASS (e.g. Tinney, Delfosse & Forveille 1997; Kirkpatrick et al. 1999). The frequency of detection in both cluster and field star surveys is now so high that brown dwarfs may actually be as common as low mass stars. For a review, see e.g. Tinney (1999) and Basri (2000).

With such high abundances, it becomes even more important to understand the origin of brown dwarfs. It has been widely assumed that brown dwarfs form a natural extension to normal stars, i.e. large cores produce massive stars, and smaller cores produce lower-mass stars (e.g. Elmegreen 1999). Alternatively, it has been suggested that substellar objects may form through instabilities in circumstellar disks (e.g. Pickett et al. 2000). In a radical departure from these views, we here suggest that brown dwarfs are stellar embryos which have been ejected as a result of close dynamical interactions between small unstable groups of nascent stellar seeds, i.e. brown dwarfs differ from hydrogen burning stars only in that dynamical interactions deprived them from gaining further mass by prematurely cutting them off from their infalling gas reservoirs (Reipurth 2000). In this paper, we examine this suggestion in some detail, and propose various observational consequences and tests.

2. DISINTEGRATING MULTIPLE SYSTEMS

The dynamics of non-hierarchical triple or higher order systems has no analytical solutions and the chaotic motions of the members can only be followed numerically and analyzed statistically; for a review see Valtonen & Mikkola (1991). The motions can be divided into three categories: *interplay*, in which the members move chaotically among each other; *close triple approach*, when all members at the same time occupy a small volume of space; and *ejection*, in which one member departs the system after exchanging energy and momentum with the two others. A close triple approach is a necessary but not sufficient condition for ejection. Ejections often lead to escape, but can also result in the formation of a hierarchical triple system, with one body in an extended orbit. The remaining two members are bound closer to each other, forming a tighter and highly eccentric binary system. Most often, although not always, it is the lowest mass member that is ejected; the escape probability scales roughly as the inverse third power of the mass (e.g. Anosova 1986). The ejected member acquires a velocity $v_{eject} \sim 15\ D_{ca}^{-1/2}$, where v_{eject} is in km s^{-1} and the closest

approach D_{ca} is in AU (Armitage & Clarke 1997). Sterzik & Durisen (1995, 1998) have performed realistic numerical simulations of triple T Tauri systems and find ejection velocities of typically 3-4 km s^{-1} but with a higher velocity tail. The decay of a triple system occurs stochastically and can only be decribed in terms of the half-life of the process. Anosova (1986) finds that within about one hundred crossing times t_{cr} almost all systems have decayed, where $t_{cr} \sim 0.17(R^3/M)^{1/2}$, and R is a characteristic length scale for the system in AU, and M is the total system mass in $M_\odot$.

Three-body dynamical simulations including substellar members have been performed by Sterzik & Durisen (1999) and their dynamical results can be summarized as *brown dwarfs are ejected because they are of low mass*, in agreement with the general theory just outlined. This is in contrast to the evolutionary scenario advocated here which can be summed up as *brown dwarfs are of low mass because they are ejected*.

3. COMPETITION BETWEEN ACCRETION AND EJECTION

3.1. *The General Problem*

The mass of an individual star formed in a small multiple system is largely determined by the competition of two independent processes: on the one hand the accretion rate, which relates to the initial core properties, and on the other hand the decay of the multiple system, which leads to protostars being ejected and thus separated from their natal mass reservoir.

Consider a core containing a number of embryos whose initial mass is much less than the mass of distributed gas in the core. The timescale on which the bulk of the mass is accreted by the various embryos is of order the dynamical timescale of the parent core (Bonnell et al. 2001a), i.e. a few times 10^5 years for canonical core properties. If the core mass divided by the number of embryos is larger than the hydrogen burning mass limit, then evidently if accretion went to completion *and* all embryos acquired their mass equally, no brown dwarfs would result. Brown dwarf production therefore requires at least one of the following conditions to be realized: (i) some embryos are ejected before the accretion process has gone to completion (i.e. the timescale for ejection is less than the timescale on which the embryo would otherwise acquire a mass equal to the hydrogen burning mass limit) and/or (ii) the embryos acquire their mass very inequitably.

A number of simulations, designed with rather different questions in mind, can be used to shed light on each of these scenarios.

In the first case, it is necessary for the ejection event to occur rapidly (i.e. on a timescale of less than the $\sim 10^5$ year timescale of the parent core). Therefore, the relevant embryos must form in a rather compact configuration (i.e. on a length scale that is much smaller than the core size). For example, Sterzik & Durisen (1995) showed that the half-life for ejection is around 10^5 years if three embryos occupy a volume of diameter around 200 AU (i.e. on a size scale of around two orders of magnitude smaller than the typical size of the parent core.) The system then consists of a central mini-cluster of embryos which is fed mass from the infall of the surrounding envelope. [To date, calculations of infall onto multiple systems have been restricted to co-planar hierarchical systems (Smith, Bonnell & Bate 1997), and so are not relevant to the current non-hierarchical situation]. Numerical simulations of collapsing cores (e.g. Burkert & Bodenheimer 1993) show that the formation of a disk may be accompanied by the production of multiple fragments in non-hierarchical orbits, whereas star-disk and disk-disk interactions may likewise generate additional small fragments on the size scale of disks (Boffin et al. 1998, Watkins et al. 1998a,b). Fragmentation into even smaller volumes may be enhanced by magnetic fields (Boss 2000). Altogether, it would seem straightforward to achieve the initial conditions for the ejection model considered here.

In the second case, it is not necessary that the embryos form in a compact volume within the protostellar core, since an embryo does not have to be ejected in order to avoid reaching the hydrogen burning mass limit. [One may instead envisage a situation similar to the 'prompt initial fragmentation' model proposed by Pringle (1989) in which fragments are seeded by existing structure in the core]. In this case, it is enough if more gentle encounters perturb an embryo into an orbit where it does not intersect the densest part of the mass reservoir. Such a situation has an inbuilt feedback, since once an embryo has fallen behind in the race to acquire mass, it is more readily deflected away from the central densest regions. Likewise, embryos which acquire an early start in the mass race remain in the centre and preferentially intersect the infalling mass flow. This runaway to disparate masses is the basis of the competitive accretion scenario explored in a series of papers by Bonnell and collaborators (Bonnell et al. 1997, 2001a, 2001b). Of greatest relevance to the present discussion of small group dissolution are the simulations contained in Bonnell et al. (1997) which follow the evolution of cores containing 5-10 embryos initially distributed throughout the core volume. The trajectories and mass acquisition histories of the embryos clearly demonstrate the evolutionary path described above. Although these are only pilot simulations, and cannot be used to draw statistical inferences about the resulting mass distributions of stars, it is notable that the simulations do show a significant number of stars acquiring less than 10% of the mean mass of stars in the clusters (corresponding roughly to the mass range of brown dwarfs: see, for example, Figure 2 of Bonnell et al. 1997 in which 2 out of the 10 objects end up in this category).

Although in the second case, an embryo can remain low mass without being ejected (on the mass acquisition timescale of $\sim 10^5$ years), the non-hierarchical situation is ultimately unstable, so that on timescales not much longer than this the system will break up into a system of binary and single stars. Thus in either case, the expected outcome is the production of a population of 'stars' whose mass is much less than the average mass produced by the core - i.e. objects we might loosely identify with brown dwarfs and very low mass stars. The critical difference between these two cases is the expected ejection velocity of the "brown dwarfs": for the case of the initially compact embryo configuration, the typical separations of close encounters are two orders of magnitude less than for the case that embryos are initially distributed throughout the core, and this translates into ejection velocities that are an order of magnitude greater (see Sects. 4.1 and 4.4).

The rough estimates presented here suggest that brown dwarfs could be common, maybe as common as normal stars, which is indeed what some recent surveys suggest. However, the only proper way to estimate the efficiency of this mechanism for producing brown dwarfs is through detailed numerical simulations of the dynamical evolution of small N-body systems in a time-variable potential and including the presence of circumstellar material. Though a number of simulations have attempted to capture aspects of this complex problem, there is clearly much more to be done in this area.

3.2. *A Toy Model*

To get a feeling for the time scales involved, consider the following order-of-magnitude estimates. Assume a flattened cloud is collapsing with a time-averaged mass infall rate $\dot{M}_{infall} \sim 6 \times 10^{-6}(T/10K)^{3/2}$ M$_\odot$ yr^{-1}, as derived by Hartmann, Calvet & Boss (1996). A 1 M$_\odot$ cloud at 10 K would then take 1.7×10^5 yr to collapse. Assume that the collapse fragments into a number N_{mul} of stellar embryos and that the infalling mass is distributed among them according to their mass ratios $q_i = M_i/M_{prim}$ (which may be time-dependent), where $1 \leq i \leq N_{mul}$, and M_{prim} is the time-dependent mass of the most massive embryo. Further assume that a part f of the infalling gas is lost in outflow activity, where we adopt f~0.3. The growth rate of the ith embryo is then $\dot{M}_i = \dot{M}_{infall} \times (1-f) \times q_i/N_{mul}$, and for the simplest case where $N_{mul} = 3$ and $q_i = 1$ it will then take a typical embryo about 6×10^4 yr to grow beyond a substellar mass.

If the three stellar embryos occupy a volume with diameter 200 AU, and if we consider a total mass in the range 0.06 to 0.24 M$_\odot$, then the characteristic crossing time $t_{cr} \sim 0.17(R^3/M)^{1/2}$ is between 1000 yr and 2000 yr. If, on the other hand, the configuration is tighter, occupying a volume with a diameter of only 20 AU, then T_{cr} is merely 30-60 yr.

The usual decay equation is $n_t/n_o = exp(-0.693t/\tau)$, where τ is the half-life of the decay. In their numerical simulations, Sterzik & Durisen (1995) found that about 95% of all systems had decayed after about 100 crossing times. This allows us to link the crossing time and the half life of the decay, $\tau = 23.1t_{cr}$, so that to first order $n_t/n_o = exp(-0.18\dot{M}_{infall}^{1/2}(1-f)^{1/2}N_{mul}^{-1/2}R^{-3/2}t^{3/2})$.

While the stellar embryos are still very small, the crossing time, and therefore the half life, is extremely long, i.e. the embryos do not effectively start to interact until a time T$_i$ when they have a certain mass. When the embryos are very small, their awareness of each other is limited because they are surrounded by the massive infalling envelope, and this further adds to T_i. But as the envelope material thins out and the embryo masses increase, their dynamical interactions become important. A more precise value of T_i can only be determined by numerical experiments.

We will say that there is a reasonable chance that a brown dwarf is ejected if the half-life τ of the decay is less than $T_* - T_i$, where T_* is the free-fall time required to build up a multiple system of objects of average mass 0.08 M$_\odot$, i.e. $T_* = (N_{mul} \times 0.08)/\dot{M}_{infall}$. If the ejection occurs at a time later than T_*, then the ejected object is a star. In either case it has been assumed that the amount of circumstellar material the ejected object brings with it is small.

Figure 1 shows a simple, schematic presentation of these processes in a growth vs decay diagram, based on the values already discussed. The stapled line represents the growth of an embryo, which reaches the stellar mass threshold after 6×10^4 yr. The solid curve shows n_t/n_o, which is a measure of the probability that the multiple system has not yet decayed. To be conservative, we have assumed the embryos occupy a volume of diameter 200 AU, resulting in a large t_{cr}. The time when interactions begin to take place, T_i, has arbitrarily been set to 3×10^4 yr. In the particular example shown, about one third of a population of triple systems would have decayed before the expulsed member reached the stellar mass limit.

An important issue concerns the rate at which mass is accreted. The mass accretion rate adopted in Figure 1 is constant, in accordance with Shu (1977), but studies of shock-induced collapse suggest that infall might start with a powerful burst, briefly reaching values as high as 10^{-4} M$_\odot yr^{-1}$, and subsequently decreasing (e.g. Boss 1995). If so, an embryo might much more quickly reach and exceed the stellar mass limit, leaving less time for the ejection of brown dwarfs.

This is, however, *not* a problem for the ejection scenario, because each of the following four physical processes will allow more time for ejection. Firstly, the infalling mass is distributed among the stellar seeds, and if N_{mul} is higher than three, T_* becomes correspondingly higher. Secondly, in the calculations above we have for simplicity assumed that the components of newborn multiple systems have equal access to growth from infalling material, but as discussed in Sect. 3.1, competitive accretion is likely to be a very important process (Bonnell et al. 1997), leading to q_i different from 1, and this would leave one or more embryos as substellar objects for extended periods of time. Third, if embryos are born in a more compact rather than a wide configuration (Sect. 3.1), then the crossing time decreases dramatically, leading to enhanced probability of very rapid ejection, on timescales of just a few thousand years. Finally, it is conceivable that stellar embryos may be formed over a period of time, with late-forming embryos being rapidly ejected by their more evolved siblings.

4. OBSERVATIONAL CONSEQUENCES OF THE EJECTION MODEL

In the following, we outline a number of issues relevant to current studies of brown dwarfs as seen from the perspective of the ejection model.

4.1. *Detecting Brown Dwarfs near Embedded Sources*

All stars, as they form initially as stellar embryos and rapidly gain mass through infall, must at some early point pass from substellar to stellar mass objects. Therefore, if isolated brown dwarfs are the result of the disintegration of a system of multiple stellar embryos, the moment of decay must take place very early in the infall process, and it thus appears likely that brown dwarfs are ejected during the Class 0 phase.

It follows that *in order to find the very youngest brown dwarfs one should search near Class 0 sources*. The number of Class 0 sources known is limited, and suggests that any attempt to compare decay calculations with observations will be severely limited by small number statistics. To get a practical sense of the observed separation between a nascent brown dwarf and its siblings, assume that it is observed at a time t [yr] after ejection and moving with the space velocity v [km s^{-1}] at an angle α to the line-of-sight in a star forming region at a distance d [pc]. Then the projected separation s in arcsec is $s = 0.21\ v\ t\ d^{-1}\ sin\alpha$.

As an example, assume that a brown dwarf is moving out of a nearby ($d \sim 130$ pc) cloud at an angle of 60^o to the line-of-sight with a space velocity of 3 km s^{-1}. At a time of only 10^4 yr after ejection, the brown dwarf is already 42 arcsec from its site of birth, and after 10^5 yr, when the embedded phase of the original Class 0 source is about to end, the brown dwarf is 7 arcmin away, and its origin is soon lost in the mist of time.

Half of all ejected brown dwarfs will move into the cloud from which they formed. Such objects will be detectable only as highly extincted and weak infrared sources.

The rather high ejection velocities quoted above correspond to brown dwarfs ejected from a compact configuration (see Sterzik & Durisen 1998) and one sees that one has little chance

of associating such ejected objects with the Class 0 star at an age comparable with the average age of Class 0 sources. If, however, brown dwarfs are ejected by the softer interactions envisaged in the competitive accretion scenario (see Section 3) then their ejection velocities are typically smaller, due both to the dissipative effects of gas drag and to the larger mean encounter distances in this case. The ejection velocities have not been quantified in this case, but rough estimates suggest that they may be only of order a few times 0.1 km s^{-1}. In this case, therefore, one would expect to detect one or more brown dwarfs around any given Class 0 object.

4.2. *Binary Brown Dwarfs*

As more brown dwarfs become known and more detailed studies of individual objects are undertaken, the number of known brown dwarfs paired in binaries is certain to increase (e.g. Martín et al. 2000; Reid et al. 2001). Among the first identified bound pairs of brown dwarfs is PPl 15, which has an orbital period of six days (Basri & Martín 1999), and other pairs have been recently reported (e.g. Martín, Brandner & Basri 1999).

Intriguingly, there is gathering evidence that whereas close pairs may be common (comparable with the binary fraction for solar type stars), there is a striking absence of wider pairs: to date, no brown dwarf binaries have been detected with separations larger than 23 AU, despite a lack of any obvious selection bias against the detection of such binaries (Martín et al. 2000). The fact that this apparent dearth of wider brown dwarf pairs is found both in the field and in clusters, hints that its origin is not due to the larger scale environment, but may reflect smaller scale processes that are common to both environments. In the context of the present paper, we would argue that the small scale clustering is ubiquitous (regardless of whether the parent regions survive as large scale bound clusters) and that any observational signatures of this origin would be expected in both field and cluster environments. [Note that although some young clusters such as the Orion Nebula Cluster show no hint of primordial sub-clustering (Bate, Clarke & McCaughrean 1999), there is ample time for such clustering to have dissolved over the 2 Myr age of the cluster (Scally, in preparation)]

It is clear, however, that purely point mass dynamical interactions will not produce brown dwarf binaries. Such interactions give rise to a dynamical biasing (McDonald & Clarke 1993), such that the resultant binary is usually composed of the most massive two members of the mini-cluster (van Albada 1968). McDonald and Clarke showed that under this assumption binaries comprising two brown dwarfs would essentially never be formed, a result confirmed by the more recent numerical simulations of Sterzik & Durisen (1998).

The situation is, however, different in the case that cluster dissolution is associated with dissipative interactions between the stars (embryos). An obvious source of such dissipation is provided by the presence of extended disks around each object, which exert a drag on neighboring stars whose orbits intersect the disk (Clarke & Pringle 1991a, 1991b, Hall, Clarke & Pringle 1995). McDonald & Clarke (1995) modeled the disintegration of small multiple systems in which the dynamics was crudely modified by parameterized star-disk interactions. They showed that the dynamical bias is considerably weakened in this case: dissipative interactions harden the resulting binaries and allow for the survival of low mass pairs that would otherwise have been broken up in dissipationless environments. Nevertheless, the predicted binary fraction for brown dwarfs in these simulations is still low (around 5%). More realistic calculations (Delgado, in preparation) are required in order to investigate whether this represents a serious objection to the ejection model.

Whatever the origin of brown dwarf binaries in mini-clusters, they clearly have to be rather close in order to survive the ejection. More specifically, Sterzik & Durisen (1998) found that the binaries that survive had separations not exceeding roughly one third of the mini-cluster radius. The apparent observed dearth of binary brown dwarfs with separation greater than $20-30$ AU would then certainly be consistent with the scenario that brown dwarfs were ejected from a compact configuration (i.e. within a volume of radius ~ 100 AU).

A further criterion necessary for the survival of brown dwarf binaries is that after formation they do not continue to accrete beyond the hydrogen burning mass limit. In order for this to be the case, it is probably necessary for the interaction giving rise to the binary to eject it in the process. Again, further simulations will clarify if this is feasible.

4.3. *Brown Dwarfs as Companions to Normal Stars*

Many of the earliest searches for brown dwarfs were done towards main sequence stars or white dwarfs, and their mostly negative outcome added to the early speculations that brown dwarfs are rare. We now know, of course, that brown dwarfs are not rare, only as companions to other stars, the “brown dwarf desert” (Marcy & Butler 1998). Complete references to these searches are given by Basri (2000), who notes that the incidence of brown dwarf companions to stars with masses of 0.5 $M_\odot$ or more does not exceed 1%.

If brown dwarfs are formed as stellar embryos which were prematurely ejected, this observational result is readily explained. If these stellar embryos had *not* been ejected, they would have continued to accrete matter from the infalling gas, and eventually would have passed from the substellar to the stellar regime. Indeed, in the ejection model, the problem is not to explain the absence of brown dwarfs around more evolved stars, but rather to explain how any brown dwarf could be still bound in such a system, because continued accretion on to both of the binary components would raise the brown dwarf companion above the hydrogen burning mass limit. There are two different approaches to this.

In the first scenario, we must assume that binaries consisting of a brown dwarf and a main sequence star must have been ejected very early from the mini-cluster, in precisely the same manner discussed in Sect. 4.2 for pairs of brown dwarfs, except that in this case one of the components happens to have already exceeded the hydrogen burning limit by the time of ejection. Since statistically the lightest members of a mini-cluster are more likely to be ejected, it follows that binaries with a main sequence star and a brown dwarf are more likely to have a very low mass star like an M dwarf as a member than a more massive star like a G dwarf. Within the limited statistics available so far, this indeed seems to be the case (Rebolo et al. 1998).

In the second scenario, competitive accretion in a mini-cluster creates a group of objects with a wide range in masses. As the small N-body system dissolves through dynamical interactions, the formation and subsequent ejection of binary systems may be influenced by a dynamical bias against binaries with very low mass companions. In the case of purely point mass gravitational encounters, brown dwarfs should rarely be companions to normal stars (McDonald & Clarke 1993), since the relatively fragile nature of such extreme mass ratio binaries

makes them vulnerable to exchange reactions with other more massive stars in the newborn multiple system. The observation of at least a small number of such pairs might imply a role for dissipative interactions which harden the resulting binary and permit its survival: in the simulations of McDonald & Clarke (1995), which employed very massive and extended disks, large numbers of low mass stars or brown dwarfs ended up as companions to solar type stars. The fact that, observationally, such pairs are *not* plentiful suggests a more limited role for dissipative interactions in real systems.

Because the lowest mass members of a multiple system have a much increased chance of being ejected, it follows that if giant planets orbiting other stars were formed as stellar embryos, then they should be exceedingly rare. This is obviously contrary to the observation of numerous giant planets around stars, and it suggests that brown dwarfs and giant planets must form in two different processes.

4.4. *Kinematics of Brown Dwarfs*

If brown dwarfs are ejected stellar embryos, they should carry kinematic evidence reflecting their origins in small multiple systems. To first order, the ejected member from such a system acquires a velocity comparable to the velocity attained at pericenter in the close triple encounter. Low mass ejected members will therefore generally have higher velocities than higher mass objects.

Whether such an ejection history is likely to be detectable, through radial velocity and proper motion measurements of brown dwarfs, depends on the magnitude of the ejection velocities (which themselves depend on the closeness of triple encounters) and the general level of stellar motions in the star forming complex. For example, in clusters such as Orion or the Pleiades, where the velocity dispersion of stars in the large scale cluster potential is several km s^{-1}, brown dwarfs ejected at such speeds from primordial mini-clusters would leave no kinematic imprint. Note that the very existence of brown dwarfs in the Pleiades means that retained brown dwarfs must have been ejected at less than the cluster's escape velocity; in practice, even in the compact simulations of Sterzik & Durisen (1998), most brown dwarfs would be retained in the Pleiades. There may, however, be a significant tail of brown dwarfs ejected at higher velocities, which would populate the outer reaches of the Pleiades. Numerical simulations of the Pleiades that do *not* include primordial sub-clustering (Fuente Marcos & Fuente Marcos 2000) indicate that very few brown dwarfs are expected to be ejected by subsequent encounters within the Pleiades. Hence the detection of a brown dwarf halo around the Pleiades (or objects with discrepant proper motions) would provide unambiguous evidence of their origin in very compact mini-clusters. Further brown dwarf searches in the vicinity of the Pleiades (e.g. Bouvier et al., in preparation) are therefore likely to be particularly valuable.

Further constraints on the kinematic history of brown dwarfs are provided by their spatial distributions within star formation regions. For example, Hillenbrand & Carpenter (2000) have shown that in the core of the Orion Nebula Cluster, the mass function turns over at around 0.15 $M_\odot$. Given that there is evidence for mass segregation amongst more massive stars in the ONC (Hillenbrand & Hartmann 1998), it is obviously of great interest to determine if the substellar mass function has a similar form at larger radii in the cluster. In the case of Taurus (where the stars are not mutually bound) it is tempting to speculate that the paucity of brown dwarfs recently reported by Luhman et al. (2000) may be due to their higher ejection velocities, so that they have already left the region within which the bulk of T Tauri stars are currently concentrated.

It should be emphasized that brown dwarfs in very massive and/or very old clusters have velocities that are higher because their kinematics have been dominated by two-body relaxation. Therefore, such clusters should *also* be surrounded by a halo of brown dwarfs, but not because of their high ejection velocities. A proper test of the ejection scenario is made only by finding a halo of brown dwarfs around clusters small enough or young enough that relaxation has not yet dominated their kinematics. With regard to old brown dwarfs in the field, these have not been dynamically relaxed, but the majority must have evaporated from large clusters, in the process losing their original kinematic history (Spitzer & Harm 1958).

4.5. *Substellar Equivalents to the Classical T Tauri Stars*

Classical T Tauri stars show emission line characteristics and veiling which identify them as young accreting objects (Herbig 1962). The source of this accretion is a circumstellar disk. If brown dwarfs are ejected stellar embryos, then their disks are likely to be pruned during the close interactions that ejected them. Armitage & Clarke (1997) showed that very close encounters, which truncate the disks to radii of a few AU, could promote the rapid decline of classical T Tauri star characteristics thereafter and one might on these grounds expect that all but the very youngest brown dwarfs are unlikely to show any of the spectroscopic signatures of infall and outflow which we have come to associate with extremely young stellar objects. This appears to be consistent with current observations of young brown dwarfs (Martín 2001). In the case of ejected brown dwarfs, an empirical upper limit on expected encounter separations may be provided by the observed lack of brown dwarf binaries at separations greater than $20 - 30$ AU. Further modeling is required in order to quantify how quickly accretion characteristics would be expected to decline following brown dwarf ejection: we, however, point out that because of the draining of the pruned disk, and because ejected stars have no source of disk replenishment, it may well be difficult to find the substellar equivalents of classical T Tauri stars, except perhaps as newly ejected objects located in the vicinity of Class 0 sources.

A further issue is the effect of ejection and disk pruning on the rotation of brown dwarfs, since in many models the disk plays the major role in braking young stars (Königl 1991, Cameron & Campbell 1993, Armitage & Clarke 1996). One might thus expect that ejected brown dwarfs in star forming regions should be rapidly rotating (i.e. at speeds close to break up). However, it turns out that extremely close encounters, even at the sub-AU level, are required in order to significantly affect disk braking, at least in the case of more massive stars (see the discussion in Clarke & Bouvier 2000). Further calculations using brown dwarf parameters and plausible enounter distances, are required before one can make firm predictions of the importance of this effect, although the *sign* of the prediction (a tendency towards more rapid rotation) is clear.

4.6. *The Low-Mass End of the IMF*

Numerous studies have explored the origin of the initial mass function (see e.g. Kroupa 1995; Larson 1999; Elmegreen 2001). Such analyses have been greatly helped by the increasingly accurate determinations of the mass function reaching

into the very low mass and substellar regimes (e.g. Reid et al. 1999, Luhman et al. 2000, Najita et al. 2000, Hillenbrand & Carpenter 2000, Muench, Lada & Lada 2000). These studies have firmly established that the standard Salpeter power law slope of the IMF at higher masses gives way to a much shallower slope at lower masses or even a turn-over. While the main power law slope probably is related to the hierarchical structure of interstellar clouds, the flat part of the IMF at lower masses may result from a second, unrelated, physical process (e.g. Elmegreen 2000).

The ejection model can naturally produce the observed turn in the IMF . With reference to Figure 1, the shape of the very low mass end of the IMF is significantly influenced by the difference between T_i and T_*. If T_i should be greater than T_* all objects ejected would be low mass stars. If interactions occur even just slightly before T_*, the steep decline of n_t/n_o ensures that a population of brown dwarfs will come into existence. And if $T_i << T_*$, brown dwarfs will be abundant.

5. DO LOW MASS STARS FORM IN SMALL MULTIPLE SYSTEMS?

In recent years it has been increasingly well documented that binarity is common among pre-main sequence stars and probably higher than among main sequence stars (e.g. Reipurth & Zinnecker 1993, Ghez, Neugebauer & Matthews 1993, Köhler & Leinert 1998). More recently, an analysis of deeply embedded outflow sources has revealed an *observed* binary frequency of around 80%, with half in higher order systems (Reipurth 2000).

On the theoretical side, there is growing consensus that fragmentation during the protostellar collapse phase is the principal mechanism for forming binaries and multiple systems (e.g. Bodenheimer et al. 2000, Bonnell 2001, Whitworth 2001), although the formation of close binary stars may require additional steps, as for example dynamical interactions between the nascent stars.

For brown dwarfs to be formed as ejected stellar embryos, close triple approaches must occur very early in the infall process. This is greatly facilitated if from the outset stellar seeds are formed close to each other. In this context it is of interest that the latest three-dimensional calculations of fragmentation in a collapsing core including magnetic fields show that magnetic tension helps avoiding a central density singularity (Boss 2000). These models suggest that fragmentation leads to a transient quadruple system. This is the situation which is ideal for dynamical interactions resulting in the early expulsion of a stellar embryo.

Dynamical interactions between members of small multiple systems are well studied and it is incontrovertible that they sometimes must play a role during the star formation process. The issue is therefore not *whether* stellar embryos can be ejected from a nascent multiple system, but rather *how often* this process occurs. Larson (1972, 1995) has suggested that all stars may be born in binary or multiple systems, and the high observed multiplicity frequency of Class 0/I sources near ~80% would seem to support such a scenario (Reipurth 2000). The detection and statistical study of newborn brown dwarfs in star forming regions may therefore cast light on the general question of how low mass stars form.

6. CONCLUSIONS

We have argued here that the primary route for brown dwarf formation is *not* through the collapse of low mass cores, but that rather they are ejected as a result of encounters in multiple systems comprising a small number of stellar embryos. A number of simulations give plausibility to this picture, though the expected ejection velocities (and other properties such as the presence of accretion diagnostics, the range of binary separations and brown dwarf rotation rates) will depend on whether the embryos form on size scales comparable with the parent core ($\sim 10^4$ AU; 'prompt initial fragmentation') or on size scales of protostellar disks (~ 100 AU).

To date, simulations have tended to address the problem in piecemeal fashion, focusing separately on the roles of point mass dynamics, star-disk interactions and competitive accretion. A clear goal for theorists is more realistic simulations that integrate all these features, a goal that is becoming increasingly realizable with the aid of advances in massively parallel computer architecture. In the absence of such simulations, the predictions given above have necessarily been laced with numerous caveats. Rather than repeating these here, we set out the key observations in the coming years that will provide the datasets necessary to test the models:

1. *Brown dwarf searches in the vicinity of Class 0 sources*

A null result in this area would not contradict the ejection model, but would imply high ejection velocities (several km s^{-1}) consistent with embryos being ejected from a compact configuration (~ 100 AU). A positive result would provide strong evidence in favour of the hypothesis, but, if common, would imply rather slow ejection velocities.

2. *Brown dwarf binaries*

The apparent upper limit of $20-30$ AU on the separation of brown dwarf binaries may contain an important fossil record of a history of close encounters. Hence the placing of this result on a firmer statistical basis is an important goal. Likewise, it is important to establish whether close brown dwarf pairs are indeed as common as current estimates suggest. Although the survival of such pairs is unproblematical in the ejection model, it is not clear whether it is easy to form such low mass pairs starting from non-hierarchical initial conditions.

3. *Brown dwarfs as companions to normal stars*

The result that such companions are rare, at least in the case of solar type stars, is now well established. An important goal for simulations will be to discover whether they can simultaneously reproduce this property together with a high fraction of brown dwarfs as binary primaries (point 2. above).

4. *Brown dwarf kinematics and distributions around open clusters*

The presence of brown dwarfs in open clusters places an upper limit of several km s^{-1} on the ejection velocities of brown dwarfs that are retained in the cluster. Brown dwarf searches in the vicinity of the cluster will, however, explore a possible tail of higher velocity ejections. The existence of such a brown dwarf halo around the Pleiades, for example, would provide strong evidence in favour of the ejection hypothesis, since simulations starting from smooth initial conditions (no mini-clusters) do not eject brown dwarfs to large distances. On the other hand, a null result would not rule out the ejection hypothesis but would constrain the velocity distribution of ejected objects.

5. *Circumstellar diagnostics and rotation rates of young brown dwarfs*

Ejected brown dwarfs have suffered encounters that will have pruned their circumstellar disks. In consequence, one might expect weaker accretion diagnostics and faster rotation in young brown dwarfs compared with young stars. Further work is

required to quantify the predicted magnitude of these effects, whilst considerably more observational data is needed in this area.

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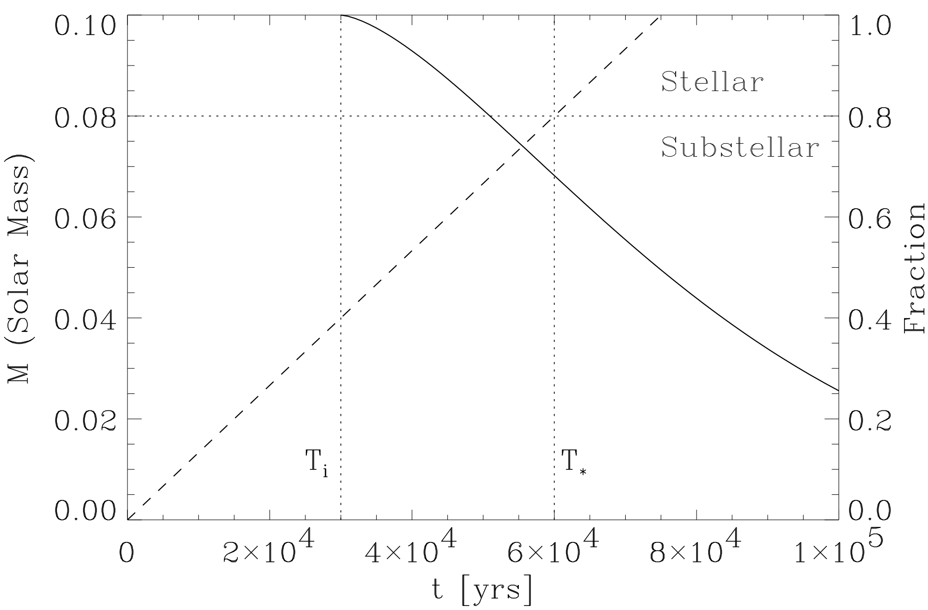

FIG. 1.— This growth vs decay diagram provides a schematic presentation of two competing processes, accretion of mass and the probability of dynamical ejection, affecting a triple system of forming stellar embryos. The stapled line indicates the growth of an embryo (assuming three embryos share a constant infall rate of $\dot{M} = 6 \times 10^{-6} M_{\odot}$ with a part f ~0.3 being lost to outflow), and the solid curve indicates n_t/n_o, the fraction of still intact systems, or equivalently the probability that a given system has still not decayed. T_* is the time when the embryo has reached a mass of 0.08 $M_{\odot}$, while T_i is the (poorly constrained) time, when the embryos have enough mass to begin dynamical interactions.